HP Ref. No. 100110275

HIGH RESOLUTION IMAGE RECONSTRUCTION

FIELD OF THE INVENTION

[0001] The present invention relates generally to digital image processing and more particularly to interpolation of a mixed resolution image sequence for high-resolution image reconstruction.

BACKGROUND OF THE INVENTION

[0002] Digital video processing refers to manipulation of the digital video bitstream. Some applications of digital video processing include standards conversion, image enhancement, high resolution image reconstruction, etc.

[0003] One known method for high-resolution image reconstruction includes the use of spatial interpolation to produce a low spatial frequency image estimate from a captured low-resolution image frame. The estimate, however, may appear blurry as it does not incorporate any related high spatial frequency information from neighboring high-resolution image frames and, consequently, does not allow large size prints of the captured low-resolution image.

[0004] Another known high-resolution image reconstruction method uses non-linear image interpolation which improves somewhat the spatial resolution of the resulting estimate, but the improvement is based on statistical information about high spatial frequency content. Furthermore, this method requires training with a set of parameters (images).

[0005] None of the known image reconstruction methods utilize high spatial frequency data from closely related high-resolution image frames.

SUMMARY OF THE INVENTION

[0006] The present disclosure is generally directed to a high resolution image reconstruction method, comprising generating at least one image sequence of temporally

related high and low resolution image frames, each of the high resolution image frames including a low spatial frequency component and a high spatial frequency component; using spatial interpolation to generate a low spatial frequency component from a low resolution image frame of the image sequence; generating a high spatial frequency component from at least one high resolution image frame of the image sequence, the high resolution image frame being closely related to the low resolution image frame; remapping the high spatial frequency component to a motion-compensated high spatial frequency component estimate of the low resolution image frame; and adding the motion-compensated high spatial frequency component estimate of the low resolution image frame to the generated low spatial frequency component of the low resolution image frame to form a reconstructed high resolution image of the low resolution image frame.

[0007] These and other aspects of the present invention will become apparent from a review of the accompanying drawings and the following detailed description of the preferred embodiments of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] The invention is generally shown by way of example in the accompanying drawings in which:

Figure 1 is a schematic representation of an embodiment of an image sensor having integrated light sensing and subsequent signal processing capability for use in accordance with the present invention;

Figure 2 is a schematic representation of an embodiment of an image downsampling module for use in accordance with the present invention;

Figure 3 is a schematic representation of an embodiment of a mixed spatial resolution image sequence in accordance with the present invention;

Figure 4 is a schematic representation of an embodiment of an image downsampling (decimation) in accordance with the present invention;

Figure 5 is a schematic representation of an embodiment of a subpixel motion processing in accordance with the present invention;

Figure 6 is a schematic representation of an embodiment of a first spatial interpolation in accordance with the present invention;

Figure 7 is a schematic representation of an embodiment of high spatial frequency image component determination in accordance with the present invention;

Figure 8 is a schematic representation of an embodiment of a second spatial interpolation in accordance with the present invention;

Figure 9 is a schematic representation of an embodiment of motion-compensated image remapping in accordance with the present invention;

Figure 10 is a schematic representation of an embodiment of motion confidence scalar field processing to form per-pixel weights α in accordance with the present invention;

Figure 11 is a schematic representation of an embodiment of high spatial frequency image component estimation using the per-pixel weights α of Figure 10 in accordance with the present invention; and

Figure 12 is a schematic representation of an embodiment of high-resolution image reconstruction in accordance with the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0009] Hereinafter, some preferred embodiments of the present invention will be described in detail with reference to the related drawings of Figures 1 - 12. Additional embodiments, features and/or advantages of the invention will become apparent from the ensuing description or may be learned by practicing the invention.

[0010] The drawings are not to scale with like numerals referring to like features throughout both the drawings and the description.

[0011] The following description includes the best mode presently contemplated for carrying out the invention. This description is not to be taken in a limiting sense, but is made merely for the purpose of describing the general principles of the invention.

[0012] Current CMOS (complementary metal-oxide semiconductor) image sensor technology allows the integration of light sensing elements and subsequent digital image signal processing. One known example of such CMOS technology allows a digital camera to switch seamlessly between high resolution and low resolution video without sacrificing the image quality of either. Specifically, signals from adjacent pixels can be combined into groups and read as one larger pixel with the size and configuration of a pixel group being variable and controlled by specialized integrated circuitry. Smaller pixels offer the benefit of higher resolution and sharper images. Larger pixels offer the benefit of higher light sensitivity required for low light still scenes and video applications. In other words, a CMOS image sensor of this type can be addressed in variable resolutions and thus, is capable of capturing a high-resolution video frame in the midst of recording motion video since pixel sizing can be done instantaneously.

[0013] Turning to Figure 1, a variable resolution CMOS image sensor, generally referred to by a reference numeral 20, preferably comprises an image sensor array 22 operatively coupled to an image downsampling module 24. Image sensor array 22 is adapted to sense light from a scene, as generally shown in Fig. 1. Image downsampling module 24 is operatively coupled between a downsampling controller 26 and RAM (random access memory) 28 (Fig. 1), i.e., the size of output images may be controlled for each frame. For example, RAM input signal 30 (Fig. 1) may be a sequence of image frames, taken 1/30 seconds apart, having different spatial resolutions such as low (640 x 480 pixels) spatial resolution image frames and high (1920 x 1440 pixels) spatial resolution image frames. A mixed spatial resolution image sequence of this type is shown schematically in Fig. 3 and generally referred to by a reference numeral 32. For example, image sequence 32 (Fig. 3) may comprise high spatial resolution image frame $\mathbf{A_0}$ followed by a series of low spatial resolution image frames $\mathbf{a_1} - \mathbf{a_3}$ which is followed by high spatial resolution image frame $\mathbf{A_4}$ which, in turn, is followed by a series of low spatial resolution image frames $\mathbf{a_5} - \mathbf{a_7}$, which is followed by high spatial resolution image frame $\mathbf{A_8}$, etc.

[0014] Figure 2 schematically illustrates an embodiment of the internal components of image downsampling module 24, namely, a low pass anti-aliasing filter 34 and a spatial

subsampler 36. Low pass anti-aliasing filter 34 is operatively coupled between image sensor array 22 and spatial subsampler 36. Spatial subsampler 36 outputs to RAM 28, as generally depicted in Fig. 2. Image downsampling is performed by filtering and subsampling the input image data. Those skilled in the art will note that the two steps may be combined for efficient implementation. According to this embodiment, the image data is convolved with a low pass anti-aliasing filtering 34. Subsampling is controlled via downsampling controller 26. For example, downsampling controller 26 may instruct spatial subsampler 36 to discard 2 of 3 samples, in each dimension, to downsample a 1920 x 1440 pixel frame to a 640 x 480 pixel frame.

[0015] Due to practical limitations in memory and bandwidth, not all captured image frames may be of high spatial resolution, i.e., only some high spatial resolution image frames such as, for example, $\mathbf{A_0}$, $\mathbf{A_4}$, $\mathbf{A_8}$, are retained with the rest being automatically downsampled (by CMOS image sensor 20) such as, for example, $\mathbf{a_1} - \mathbf{a_3}$, $\mathbf{a_5} - \mathbf{a_7}$, as generally shown in Fig. 3. High spatial resolution images such as $\mathbf{A_0}$, $\mathbf{A_4}$, $\mathbf{A_8}$ will produce good quality large size prints, i.e. may be printed directly without further processing. However, low spatial resolution images such as $\mathbf{a_1} - \mathbf{a_3}$, $\mathbf{a_5} - \mathbf{a_7}$ will not produce good quality large size prints because of low spatial resolution. On the other hand, the upper limit in size of a good quality print is determined, to a great extent, by the spatial resolution of the input image sequence. Therefore, being capable of reconstructing a good quality high spatial resolution image from an available low-resolution image is a desirable feature for digital cameras and/or image processing software.

[0016] In order to produce a good quality large size print from a low spatial resolution image frame such as, for example, $\mathbf{a_1}$, a fairly good high spatial resolution image estimate $\mathbf{\hat{A}_1}$ must be formed of the original (unavailable) image frame $\mathbf{A_1}$. In general, $\mathbf{\hat{A}_1}$ is a combination of high and low spatial frequency components, $\mathbf{\hat{A}_{1H}}$, $\mathbf{A_{1L}}$, respectively, i.e. $\mathbf{\hat{A}_1} = \mathbf{A_{1L}} + \mathbf{\hat{A}_{1H}}$. The low spatial frequency component $\mathbf{A_{1L}}$ of original (unavailable) $\mathbf{A_1}$ may be generated via spatial interpolation, as generally illustrated in Fig. 8. Specifically, available low resolution image $\mathbf{a_1}$ (Fig. 3) may be passed through a spatial upsampler 38 (Fig. 8) and a low pass reconstruction filter 40 (Fig. 8) to produce low spatial frequency component $\mathbf{A_{1L}}$ which is essentially a "blurry" version of unavailable high resolution image $\mathbf{A_1}$. Spatial upsampler 38 may be programmed to utilize standard bicubic or bilinear algorithms. Alternatively, spatial upsampler 38 may be programmed to utilize least squares error minimization algorithms to

produce a relatively sharper upsampled image in accordance with a preferred embodiment of the present invention. In particular, given a downsampling matrix B, applying its pseudo-inverse B^+ to the image calculates an upsampled approximation that is closest, in the least squares sense, to the original image.

[0017] Figure 4 schematically illustrates an embodiment of image downsampling (decimation) in accordance with a preferred embodiment of the present invention. Specifically, available and closely related high spatial resolution image $\mathbf{A_0}$ may be passed through low pass anti-aliasing filter 34 and spatial subsampler 36 (of image downsampling module 24 to produce a low spatial resolution image $\mathbf{a_0}$, i.e. a downsampled version of itself. As generally depicted in Fig. 5, the generated low spatial resolution image $\mathbf{a_0}$ (Fig. 4) and the available low spatial resolution image $\mathbf{a_1}$ (Fig. 3) may be fed into a subpixel motion processor 42 to generate subpixel accuracy motion vector field MVF_{01} and associated motion confidence scalar field CSF_{01}, respectively, i.e. each motion vector would have an associated confidence scalar value. Furthermore, the generated low spatial resolution image $\mathbf{a_0}$ (Fig. 4) may be fed into spatial upsampler 38 and low pass reconstruction filter 40, as generally illustrated in Fig. 6, to produce low spatial frequency component $\mathbf{A_{0L}}$ which is essentially a "blurry" version of originally available high spatial resolution image $\mathbf{A_0}$ (Fig. 3). The generated low spatial frequency component $\mathbf{A_{0L}}$ may then be subtracted from originally available high spatial resolution image $\mathbf{A_0}$ (Fig. 3) to obtain a residual high spatial frequency component $\mathbf{A_{0H}}$, as generally shown in Fig. 7.

[0018] In accordance with another embodiment of the present invention, the obtained residual high spatial frequency component $\mathbf{A_{0H}}$ and subpixel accuracy motion vector field MVF_{01} may be fed into a remap module 44 to produce an unweighted motion-compensated (remapped) residual high spatial frequency component $\mathbf{\hat{A}'_{1H}}$, as generally depicted in Fig. 9. Moreover, the generated motion confidence scalar field CSF_{01} may be processed via a standard weight function generator 46 to form corresponding per-pixel weights α, as generally shown in Fig. 10. Weight function generator 46 preferably includes a pixel weight look-up table (not shown). The weights α basically control how much of the remapped residual high spatial frequency component $\mathbf{\hat{A}'_{1H}}$ is added to the low spatial frequency component $\mathbf{A_{1L}}$ to form the final reconstructed high spatial resolution image estimate $\mathbf{\hat{A}_1}$. Specifically, the weights α are multiplied by the unweighted remapped residual high spatial

frequency component $\hat{A}'_{1H}$ to generate corresponding weighted remapped residual high spatial frequency component $\hat{A}_{1H}$, as generally shown in Fig. 11. The weighted residual high spatial frequency component $\hat{A}_{1H}$ and low spatial frequency component A_{1L} may then be added to obtain a fairly good high spatial resolution image estimate $\hat{A}_1$ of original, unavailable high spatial resolution image A_1. In this regard, one possible method for computing motion confidence is to apply cross-correlation matching to determine when the motion is well described by a simple translation. For motion vectors with full confidence ($\alpha = 1$) the full high spatial frequency residuals may be added. For motion vectors with low confidence, less of the high spatial frequency residuals may be added to control for possible ghosting artifacts. The degree of motion estimation accuracy essentially controls the sharpness of the reconstructed high-resolution image.

[0019] A person skilled in the art would readily recognize that the above-described novel high resolution image reconstruction method may be easily generalized to take advantage of additional high-resolution frames that might be available in the mixed pipeline output. A person skilled in the art should also recognize that given a low resolution image, the described image reconstruction method may be expanded to obtain a good high resolution image estimate not just from one neighboring (temporally related) high resolution image, but also from two or more closely related high resolution images. The novel high-resolution image reconstruction method may be used in a variety of applications such as to restore a video sequence to a higher resolution, allowing for high quality digital zoom, and/or to improve printing from video frames.

[0020] Furthermore, the above-described components of Figs. 5 - 12, inclusive, may be integrated in hardware or software form depending on desired application.

[0021] Other components and/or configurations may be utilized in the above-described embodiments, provided such other components and/or configurations do not depart from the intended purpose and scope of the present invention. While the present invention has been described in detail with regards to one or more preferred embodiments, it should also be appreciated that various modifications and variations may be made in the present invention without departing from the scope or spirit of the invention. In this regard it is important to note that practicing the invention is not limited to the applications described hereinabove. Other applications and/or alterations may become apparent to those skilled in the art.

[0022] It should be appreciated by a person skilled in the art that features illustrated or described as part of one embodiment may also be used in other embodiments. It is, therefore, intended that the present invention cover all such modifications, embodiments and variations as long as such modifications, embodiments and variations remain within the scope of the appended claims and their equivalents.